NWL Report No.1798

$\mathcal{G}_c$ TESTS OF WELDS IN TI-13V-11CR-3Al ALLOY SHEETS FROM COMPANY A AND $\mathcal{G}_c$ TESTS OF AGE-STRENGTHENED BASE METAL AND OF WELDS IN TI-6Al-4V AND TI-13V-11CR-3Al ALLOY SHEETS FROM COMPANY F - SUMMARY REVIEW OF FRACTURE TOUGHNESS RESULTS ON TITANIUM ALLOYS BEING CONSIDERED FOR SOLID-PROPELLANT ROCKET MOTOR CASES

by

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ABSTRACT

Several conditions of welds in all-beta Ti-13V-11Cr-3Al alloy were examined for fracture toughness properties. Similar tests were run on age-strengthened base metal and on annealed welds in samples from another source representing Ti-6Al-4V and Ti-13V-11Cr-3Al titanium alloys. The results were included in a summary review of fracture toughness in base metal and in welds of both alloys. At a yield strength to density ratio of approximately one million inches, there appeared to be no serious fracture toughness problems with Ti-6Al-4V alloy. Under similar conditions, the all-beta base metal (Ti-13V-11Cr-3Al) had somewhat less than optimum fracture toughness so that a construction practice practically eliminating flaws in finished cases would be required. In the all-beta welds, some practices appeared to give satisfactory toughness.

FOREWORD

The test was performed under NWL Project No. F11 "Fracture Work Rates of SP Materials" as part of SP Task Assignment No. 71402, Project Order No. 970, by authority of reference (a).

This report was reviewed by the following personnel of the Warhead and Terminal Ballistics Laboratory:

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INTRODUCTION

Company A, a titanium manufacturer, supplied welded panels of all-beta alloy, Ti-13V-11Cr-3Al, in three different sequences of welding and heat treatment. The samples covered: (1) welding followed by aging to high strength, (2) welds in the low-strength solution treated condition without further heat treatment, (3) welds in sheets age-strengthened prior to welding but with no subsequent heat treatment.

Company F, another titanium manufacturer, furnished unwelded samples of Ti-6Al-4V and Ti-13V-11Cr-3Al alloys heat treated to high strength levels. This manufacturer also supplied welded samples of each alloy in the annealed condition without further heat treatment.

These two series of tests complete an initial stage of sampling titanium alloys and fabricating and welding practices. The samples were obtained from four producers of titanium metal and two fabricators of experimental titanium rocket chambers in the period of about 1960. A general summary is given of the work on the fracture toughness of titanium for rocket motor cases.

DESCRIPTION OF MATERIAL AND PROCEDURE

Company A Samples. These were made from the all-beta alloy (Ti-13V-11Cr-3Al). Two panels each of three conditions of welding and heat treatment were received (Figure 1). The notch locations were chosen to minimize any possible effects of a mild weld porosity which was judged to be within specification limits.

Etched cross sections of the welds after $\mathfrak{K}_c$ test fracture are shown in Figures 2, 3 and 4. All welds were single pass and the melt grain size was about average. A dendritic structure pattern was brought out only in the case of aging after welding (Figure 2).

The hardness of weld cross sections in Figures 5 and 6 could be related to heat treatment based on approximate values of 300 DPH for annealed and 400 DPH for aged conditions. In panels 1 and 3 both weld and base metal had the aged hardness. Corresponding zones in panels 2 and 4 were in the soft annealed condition. In panels 6 and 7 (Figure 6, B and C), the base

metal had been aged before welding and the weld was in the annealed condition. Hardness patterns across the welds in panels 6 and 7 were used to estimate probable yield strengths at weld edge and weld center for $\mathcal{G}_c$ calculations.

Company F Samples. Unwelded samples of high-strength base metal and welded samples of alpha-beta Ti-6Al-4V alloy and of all-beta Ti-13V-11Cr-3Al alloy were tested. The $\mathcal{G}_c$ specimen layouts are shown in Figure 7. Microstructures of the high-strength (solution-treated and aged) condition of the alloys are represented in Figure 8.

Weld macrostructures of the alloys in the as-welded (annealed) condition are illustrated in Figure 9. The weld grain size was large in Ti-6Al-4V metal but this is known to have little effect on fracture toughness of welds in this alloy. The Ti-13V-11Cr-3Al weld had a moderately fine grain structure. The weld hardness patterns (Figure 10) confirmed the expected annealed conditions of weld and base metal in both alloys.

Procedure. Fracture toughness was determined with the Irwin-Kies design of center-notched strip specimen, 3 inches wide by 12 inches long. With this specimen an estimate can be made of the stress intensity factor K_c* for fast crack propagation under stress and a critical driving force $\mathcal{G}_{Nc}$ for initiation of slow crack growth from small flaws. More details on the $\mathcal{G}_c$ tests are given in Appendix B.

The center slot 1 inch long was tipped with sharp machined notches of 0.001 inch root radius. Recent trends in fracture testing of high-strength sheet materials (reference (b)) indicate that fatigue cracks should be used to tip the center slot in some materials and future tests will incorporate the fatigue notch. Present indications are that the fatigue-crack practice would result in some decrease of $\mathcal{G}_c$ values but with no major change in the relative fracture ratings of these titanium alloys.

RESULTS AND DISCUSSION

Information. The yield strength at point of fast fracture enters into calculation of fracture toughness properties. The small volume of metal in welds makes localized yield strength measurement difficult so the practice for $\mathcal{G}_c$ calculations is to use the yield strength of the adjacent base metal. Weld and adjoining base metal usually are about in the same condition

so that a satisfactory estimate can be obtained. However, in the present tests, panels 6 and 7 from Company A represented annealed welds in aged base metal which would exhibit considerable variation in the yield strength property. A practical solution was to estimate probable yield strengths from weld hardness patterns based on known relations between yield strength and hardness. Weld centers were assumed to be in the annealed condition and the weld edge properties were taken to be midway between annealed and aged yield strengths. Table 1 gives fracture toughness values recalculated from the adjusted yield strengths. Although the adjustment made little change in $\mathcal{G}_c{}^*$ and $K_c{}^*$, the beta ratio values for estimating critical crack tolerance were affected substantially. Charts (Figures 11 and 17) and discussion of panel 6 and 7 tests were based on the adjusted values from Table 1.

Results on Ti-13V-11Cr-3Al Samples from Company A. The critical fracture stress intensities ($K_c{}^*$) for crack propagation were plotted in Figure 11. When welding was the final operation so that a soft annealed metal (about 130,000 psi yield strength) was obtained in the joint, fracture toughness properties within the weld zone were practically independent of whether the base metal had been in a soft solution-treated or in an age-strengthened condition. If the panel was given a final aging treatment after welding (panels 1 and 3), poor fracture toughness properties were obtained. The latter tests represented an experimental treatment since aged welds of this alloy ordinarily are not used.

Internal flaws appear to grow slowly to a crack length of about 2t (twice the sheet thickness) before fast propagation occurs so that sufficient toughness to contain a 2t crack length is desirable. In order to meet the critical crack length tolerance of 2t for axial stress across a girth weld, a ratio of 0.9 would be required for beta value by the Irwin formula, $\beta = \frac{(K_c{}^*)^2}{t\ \sigma_{YS}{}^2}$. Beta is proportional to the ratio of plastic zone size at the crack tip to sheet thickness (reference (c)). The aged welds were unsatisfactory, with betas of only 0.3 in the center (Table 4, specimens 1 and 3). The centers of unaged welds had satisfactory average beta values ranging from 1.0 to 2.8 (Table 4, specimens 2 and 4; Table 1, specimens 6 and 7).

Values of the driving force, $\mathcal{G}_{Nc}$, for initiation of slow crack growth from a machined notch of 0.001 inch root radius were obtained by an acoustic method (reference (d)) and are reported in Table 4. There was considerable scatter in the values which ranged from 20 to 100 inch-pounds per square inch for the critical weld center area.

Results of Tests on Samples from Company F. The unwelded panels simulating cylinder wall material had been heat treated to yield strengths of 157,000 psi for Ti-6Al-4V alloy and 181,000 psi for Ti-13V-11Cr-3Al alloy. The corresponding yield strength to density ratios were 0.97 x 10^6 and 1.03 x 10^6 inches so that both alloys were within a few percent of the ratio of one million inches desired for cylinder walls of lightweight rocket chambers. At this strength-weight ratio the usual large differences in fracture toughness between these two alloys were observed as summarized below.

Alloy	Thickness (in.)	$\mathcal{G}_c$ * (in-lb/in^2)	K_c* (1000 psi $\sqrt{\text{in.}}$)	Critical Crack Tolerance Under Hoop Stress (t)
Ti-6Al-4V	0.124	1,056	132	1.82
Ti-13V-11Cr-3Al	0.124	296	66	0.34

The Ti-6Al-4V alloy with a crack length tolerance of almost 2t had a fracture toughness near the optimum for a good balance with high yield strength. With a tolerance of only 1/3t, the Ti-13V-11Cr-3Al alloy would require extreme care in manufacturing to minimize crack development from small flaws. Other tests have shown that the toughness of all-beta alloy probably would be improved if cold working were substituted for part of the age-strengthening operation. A broader comparison of these two alloys is given in the next section.

K_c* fracture toughness values in the weld zone of annealed base metal for both alloys from Company F are plotted in Figure 12. The Ti-6Al-4V panel showed consistently high toughness values in the center and edge of the weld. This was confirmed by shear values of 100 percent in the fast fracture (Table 5).

TABLE 1

ADJUSTMENT OF G_c TEST RESULTS FOR PROBABLE YIELD STRENGTHS IN THE WELD ZONE IN AGED Ti-13V-11Cr-3Al ALLOY, PANELS 6 AND 7 FROM COMPANY A

(Values in parentheses are those calculated by ordinary procedure of using the yield strength of the base metal as reported in Table 4)

Condition	Notch Location	Specimen Number	Probable(1) Yield Strength (psi)	$\mathcal{G}_c^*$ Fracture Toughness (in-lb/in^2)	K^*_{cl} Stress Intensity (1000 psi $\sqrt{in}$)	Net Section Ratio σ_{net}/σ_{YS}	β Beta Value
Solution treated, aged 72 hours at 900°F, then welded	Weld center	6-3	131,000	342 (332)	70 (69)	.572 (.482)	1.87 (1.27)
		6-4	131,000	142 (142)	45 (45)	.377 (.318)	.78 (.55)
			Average	242	58	.475	1.33
	Weld center	7-3	131,000	324 (312)	68 (66)	.559 (.435)	1.72 (.98)
		7-4	131,000	255 (236)	60 (58)	.498 (.388)	1.34 (.76)
			Average	290	64	.529	1.53
	Weld edge	6-1	143,000	300 (296)	65 (65)	.493 (.454)	1.53 (1.30)
		6-2	143,000	441 (432)	79 (78)	.592 (.545)	2.28 (1.88)
			Average	371	72	.543	1.91
	Weld edge	7-1	149,000	649 (626)	96 (94)	.674 (.597)	3.43 (2.58)
		7-2	149,000	1408 (1296)	141 (136)	.919 (.815)	7.22 (5.28)
			Average	1029	119	.797	5.33

(1) Based on hardness values across weld section related to known values of yield strength versus hardness for this alloy

The weld centers in Ti-13V-11Cr-3Al alloy gave typical low results. The weld edge values were better and an extremely high value was found in specimen W-4. As shown in Figure 13, the cause was traced to a sharply-angled juncture of heat-affected weld zone with unaffected base metal which enabled the tough base metal to reinforce the weld edge at the point of fracture.

The $\mathcal{G}_{Nc}$ values for crack initiation in Company F samples are listed below (from Table 5).

Alloy	Condition	Average $\mathcal{G}_{Nc}$ ($in\text{-}lb/in^2$)
Ti-6Al-4V	Aged base metal	271
Ti-6Al-4V	Weld center (annealed)	253
Ti-13V-11Cr-3Al	Aged base metal	80
Ti-13V-11Cr-3Al	Weld center (annealed)	35

The advantage of Ti-6Al-4V alloy in resisting propagation of cracks apparently also extends into the phenomena of initiation of fracture.

Both Company A and Company F weld test results are included with the general comparison in the next section.

Summary Review of Fracture Toughness Tests on Titanium Alloys for Rocket Motor Cases. Two main factors will be considered in summing up what has been learned about titanium for rocket motor case construction. First, in cylinder wall material, the premise is that the strength-weight characteristics should afford a ratio (σ_{YS}/ρ) close to one million inches. Second, the fracture toughness in cylinder wall and in girth weld joints should be high enough for successful fabrication and operation of the missile. The guide used for optimum fracture toughness is the minimum requirement of a 2t length tolerance for open cracks when circumferential (hoop) stress in the wall equals the yield strength of the material (corresponding axial stress across girth welds would be on the order of half of the yield stress). Crack length tolerance can be expressed by beta values and, for hoop stress, a beta of 2π is equal to a 2t tolerance. In the case of girth welds subjected to the lower axial stress, a beta of 0.9 corresponds to a 2t tolerance (formulas are given in Appendix B).

The relations of beta ratio to σ_{YS}/ρ for titanium wall material are given in Figures 14 and 15 (the numbers on the data points refer to sources listed at the bottom of this page*). In girth welds, thickness of the joined edges can be increased so that annealed yield strengths (about 130,000 psi) are satisfactory at the joint. Since strength-weight ratio is not a serious problem at this location, the beta values of simulated girth weld tests were plotted against only yield strength in Figures 16 and 17.

Fracture toughness results on Ti-6Al-4V sheet are summarized in Figure 14. With a low σ_{YS}/ρ of about 0.75 x 10^6 inches, the annealed condition is not of much interest even though crack tolerance is large. In the solution-treated and aged condition, the improved strength resulted in strength-weight ratios approximating the desired value of one million inches. A beta ratio of about 2π in the high strength condition indicated a crack length tolerance close to 2t corresponding to an optimum balance between toughness and yield strength (reference (c)). This alloy, therefore, appears to have both a strength-weight ratio and an optimum resistance to crack propagation suitable for wall construction in lightweight chambers for solid propellant rockets. The rocket casings probably would be made by machining ring-rolled heavy cylinders. A water quench is a necessary part of the heat treatment. Weld toughness will be discussed later.

The summary results on Ti-13V-11Cr-3Al alloy for use as cylinder wall material are given in Figure 15. From a rough interpolation of the data it would appear that the optimum 2t tolerance is not obtainable above a σ_{YS}/ρ of about 0.9 x 10^6 inches. High σ_{YS}/ρ values of over 1.1 x 10^6 inches were measured in some tests but the corresponding crack tolerance was considerably lower than 2t. A strength-weight ratio of one million inches, being of primary interest, will be taken as the basis for discussion. At this strength-weight level it is obvious from Figure 15 that the average crack length tolerance would be near one t. This t value corresponds to a fracture toughness probably insufficient to arrest a through crack that might grow from a small flaw under stress.

*Code for data points in Figures 14 through 17: (1) - reference (e), (2) - reference (f), (3) - reference (g), (4) - reference (h), (5) - reference (i), (6) - present report, Company A, (7) - present report, Company F.

In effect, the successful use of Ti-13V-11Cr-3Al alloy should require extreme care in material selection and chamber manufacture in order to avoid the presence of crack-starting flaws. Experimental chambers made by such a method have withstood design pressure in hydrotest (reference (h)). $\mathcal{K}_c$ tests of a cold flow-turned and aged wall sample from a missile casing which passed hydrotest indicated a crack tolerance of one t at a σ_{YS}/ρ of 1.1 x 10^6 inches. In general, this alloy shows promise of reaching high strength levels but related fracture toughness is almost certain to be a moderate value significantly below the optimum 2t criterion. The alloy has advantages of being formable by cold flow turning and of being hardenable by relatively easy heat treatment.

The seamless cylinders of high-strength titanium wall material are joined by circumferential seam welds to each other and to the spherical fore and aft end closures to form a rocket chamber. Local thickening of the edges to be joined reduces stresses operating on the weld so that the 120,000 to 140,000 psi yield strength range of annealed or as-welded titanium alloys meets the strength requirement. The strength-weight ratio σ_{YS}/ρ is not critical because of the thickened joints and of the 1:2 ratio of axial to hoop stress. The lower stress level reduces the amount of fracture toughness required to arrest crack growth from a small flaw so that a beta value of 0.9 corresponds to the desired tolerance for a 2t crack length.

As shown in Figure 16, $\mathcal{K}_c$ tests of Ti-6Al-4V welds from three sources indicated considerably more than the minimum crack length tolerance. Provided that welds are made by ordinary good practice for titanium, fracture toughness of girth welds apparently is not a problem in the use of this alloy for rocket chambers.

The fracture toughness results in girth welds of all-beta Ti-13V-11Cr-3Al alloy are illustrated in Figure 17 based on samples from five sources. The beta value of 0.9 required for a 2t crack tolerance in these welds was not exceeded consistently at any part of the yield strength range covered by the chart. Aging heat treatment after welding to yield strength levels above 160,000 psi was obviously harmful to toughness since all of the weld centers in this region were relatively brittle. This effect of aging is not serious since unaged (annealed) yield strengths are considered satisfactory with the practice of joining thickened edges. Based on beta values in annealed welds, several apparently satisfactory individual welding practices were indicated. The brief sampling plan did not lead to definition of

optimum welding conditions. The general characteristics of all-beta welds have been discussed in other reports (reference (j)). Flaw content of the weld center obviously ought to be kept low since there is little excess of toughness above the minimum requirement. With fracture toughness tests to establish and control a selected welding practice, it would seem that satisfactory welds could be made in all-beta alloy.

CONCLUSIONS

The tests of welded all-beta Ti-13V-11Cr-3Al samples supplied by Company A indicated that the critical weld center locations met minimum fracture toughness requirements for motor case girth welds if left in the as-welded (annealed) condition. Welds aged to high yield strength were unsatisfactory.

Samples from Company F comparing Ti-6Al-4V and Ti-13V-11Cr-3Al alloys showed the typical advantage of Ti-6Al-4V alloy from a fracture toughness standpoint both in base metal aged to high strength and in annealed welds.

Based on samples from a number of titanium manufacturers and fabricators, it was concluded generally that Ti-6Al-4V alloy presented no serious problems from a fracture toughness standpoint in reaching a yield strength to density ratio of about one million inches in rocket motor cases made by joining seamless cylinders with thickened girth welds.

A similar survey of Ti-13V-11Cr-3Al all-beta alloy samples showed no difficulty in reaching high strength in the cylinder wall but fracture toughness was below the optimum so that careful manufacture would be required to eliminate flaws which might initiate cracking. Fracture toughness for thickened girth welds was not consistently above the minimum requirement but it was also indicated that satisfactory girth weld practices could be selected by tests.

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(c) Irwin, G. R., "Fracture Testing of High-Strength Sheet Materials Under Conditions Appropriate for Stress Analysis", Naval Research Laboratory Report No. 5486, July 1960
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(f) NWL Dahlgren Technical Memorandum No. T-14/60 (U)
(g) NWL Dahlgren Technical Memorandum No. T-35/60 (U)
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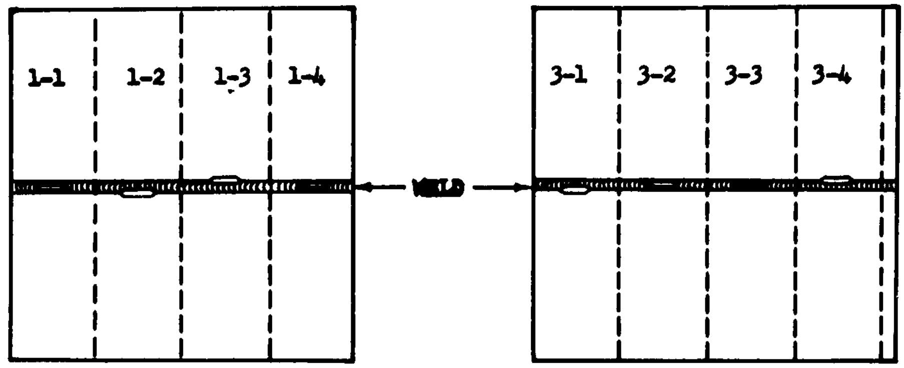
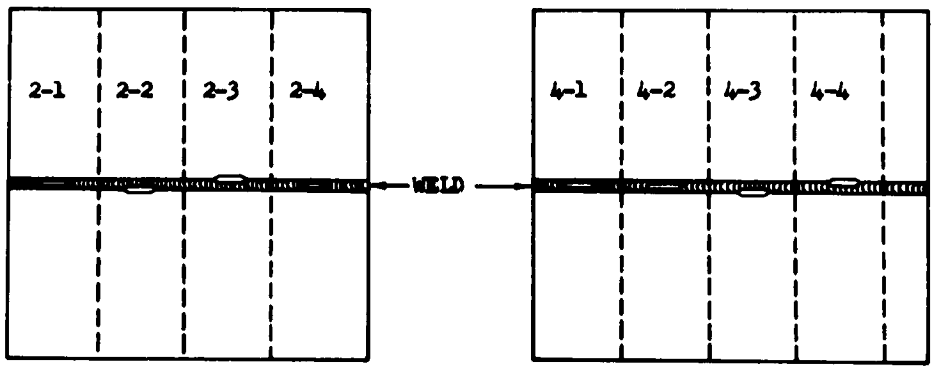
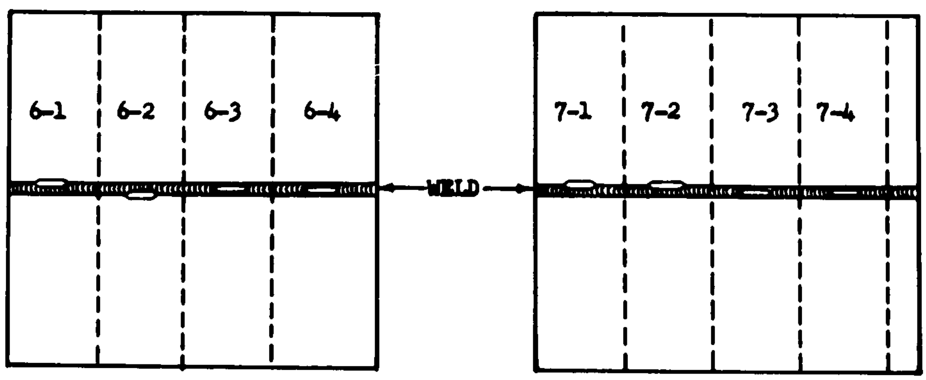
APPENDIX A



A. SOLUTION TREATED, WELDED, THEN AGED 72 HOURS AT 900°F PLUS 5 MINUTES AT 1050°F



B. SOLUTION TREATED AND WELDED



C. SOLUTION TREATED, AGED 72 HOURS AT 900°F THEN WELDED

FIGURE 1

TEST LAYOUT OF WELDED PANELS OF Ti-13V-11Cr-3Al ALLOY SUPPLIED BY COMPANY A

(A) Specimen 1-3, notch at edge of weld, G_c fast fracture on left end.

(B) Specimen 3-4, notch at edge of weld, G_c fast fracture on left end.

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FIGURE 2

CROSS SECTIONS OF TYPICAL WELDS ETCHED TO SHOW GRAIN STRUCTURE IN WELD AND HEAT AFFECTED ZONES OF Ti-13V-11Cr-3Al ALLOY SUPPLIED BY COMPANY A

Solution treated, welded, then aged 72 hours at 900°F plus 5 minutes at 1050°F

Face of weld at top, "C" etch, X8

(A) Specimen 2-3, notch at edge of weld, G_c fast fracture on left end.

(B) Specimen 4-3, notch at edge of weld, G_c fast fracture on left end.

PHD-56413-9-61

FIGURE [illegible]

CROSS SECTIONS OF TYPICAL WELDS ETCHED TO SHOW GRAIN STRUCTURE IN WELD AND HEAT AFFECTED ZONES OF Ti-13V-11Cr-3Al ALLOY SUPPLIED BY COMPANY A

Solution treated and welded

Face of weld at top, "C" etch, X8

(A) Specimen 6-2, notch at edge of weld, G_c fast fracture on left end. Small spherical cavity (arrow)

(B) Specimen 7-2, notch at edge of weld, G_c fast fracture on left end.

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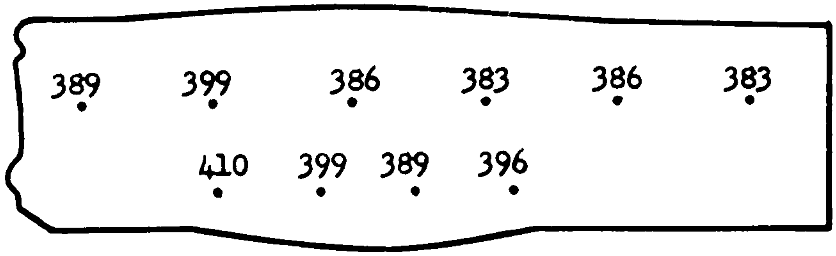
FIGURE 4

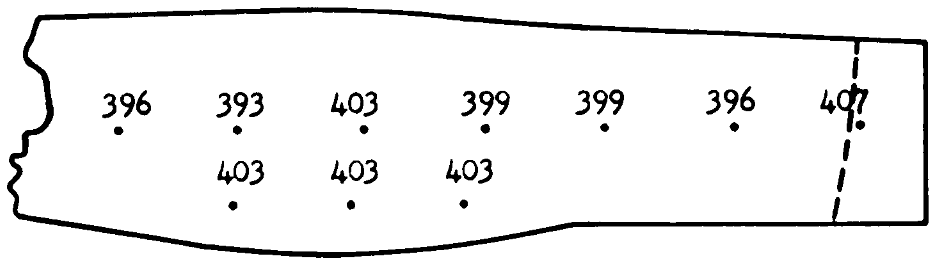
CROSS SECTIONS OF TYPICAL WELDS ETCHED TO SHOW GRAIN STRUCTURE IN WELD AND HEAT AFFECTED ZONES OF Ti-13V-11Cr-3Al ALLOY SUPPLIED BY COMPANY A

Solution treated, aged 72 hours at 900°F then welded

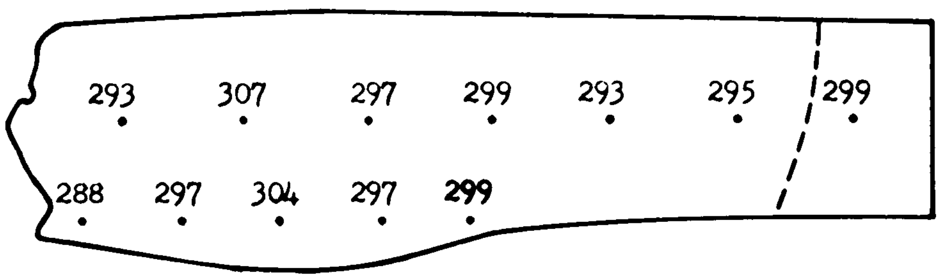
Face of weld at top, "C" etch, X8



(A) Specimen 1-3. Solution treated, welded, then aged 72 hours at 900°F plus 5 minutes at 1050°F. (Photo, Figure 2A)



(B) Specimen 3-4. Same heat treatment as (A) above. (Photo, Figure 2B)

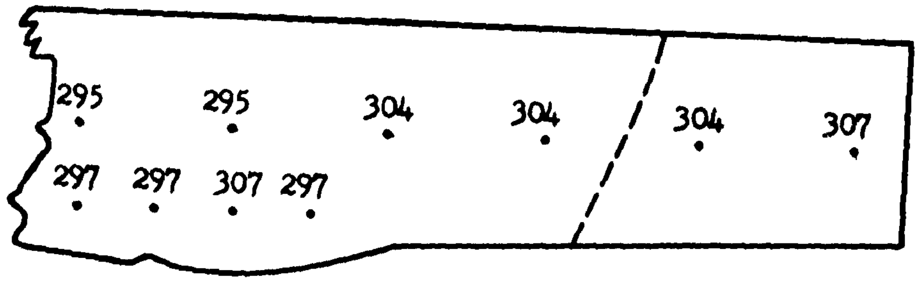


(C) Specimen 2-3. Solution treated and welded. (Photo, Figure 3A)

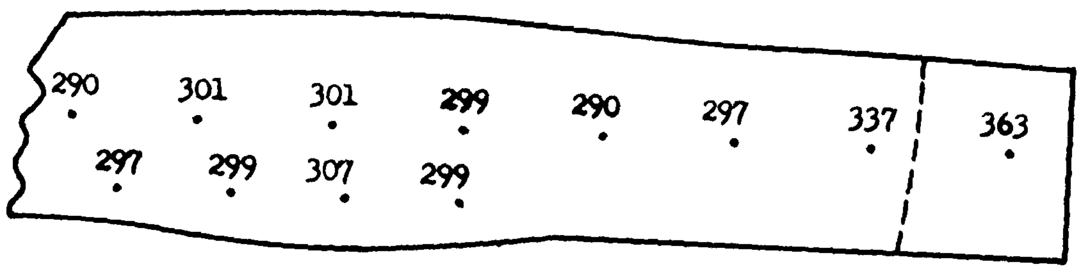
FIGURE 5

HARDNESS TESTS ACROSS WELDS IN TITANIUM ALLOY Ti-13V-11Cr-3Al SUPPLIED BY COMPANY A

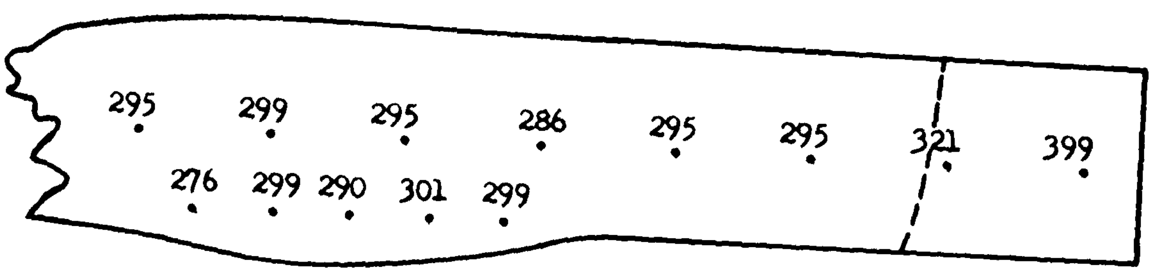
Vickers DPH Taken 2 mm Apart, 10 Kg. Load, X8



(A) Specimen 4-3. Solution treated and welded.
(Photo, Figure 3B)



(B) Specimen 6-2. Solution treated, aged 72 hours at 900°F then welded. (Photo, Figure 4A)

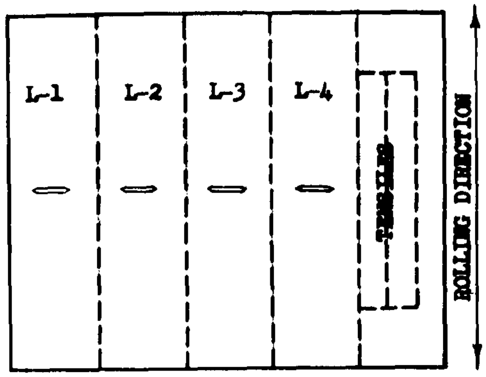


(C) Specimen 7-2. Same heat treatment as (B) above.
(Photo, Figure 4B)

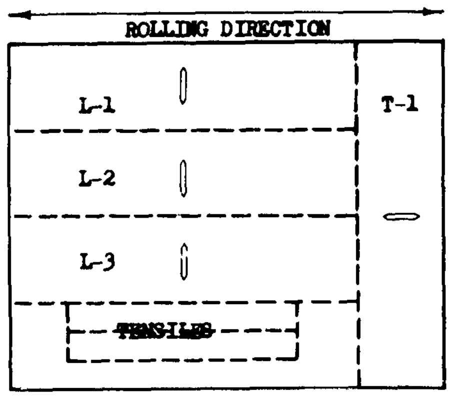
FIGURE 6

HARDNESS TESTS ACROSS WELDS IN TITANIUM ALLOY Ti-13V-11Cr-3Al
SUPPLIED BY COMPANY A

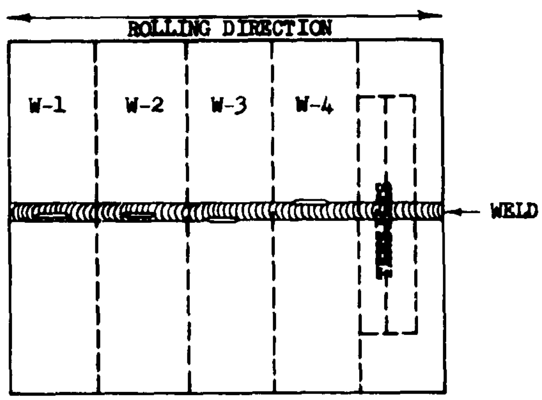
Vickers DPH Taken 2 mm Apart, 10 Kg Load, X8



A. Ti-6Al-4V ALLOY, 0.125 INCH NOMINAL THICKNESS, SOLUTION TREATED AND AGED.



B. Ti-13V-11Cr-3Al ALLOY, 0.125 INCH NOMINAL THICKNESS, SOLUTION TREATED AND AGED.

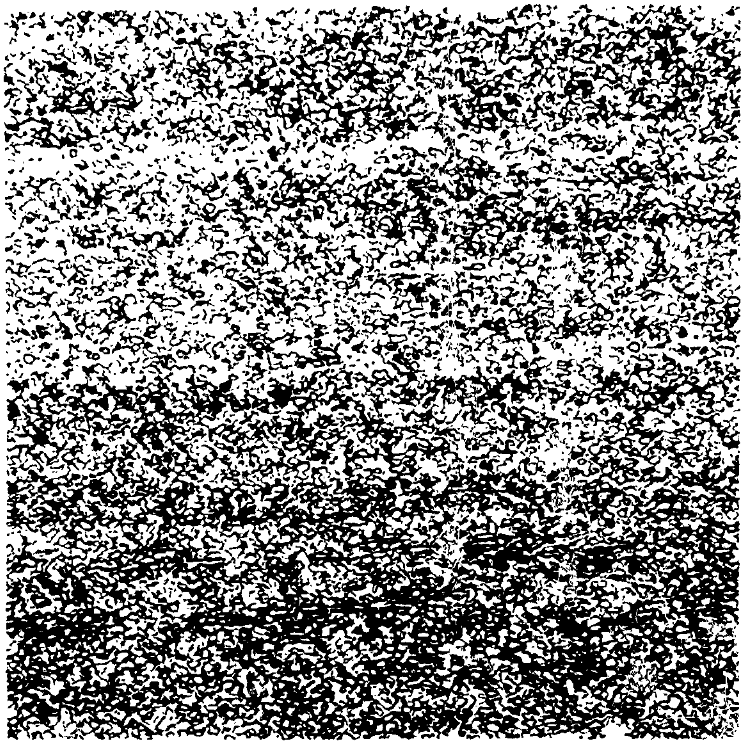


C. BOTH ALLOYS, Ti-6Al-4V AND Ti-13V-11Cr-3Al, 0.125 INCH NOMINAL THICKNESS, ANNEALED, WELDED AS SHOWN.

FIGURE 7

TEST LAYOUT OF PANELS SUPPLIED BY COMPANY F

All panels were 12 by 15 inches



(A) Ti-6Al-4V Alloy; hot rolled, solution treated and aged condition. ASTM micro grain size number 10. Hardness 375 Vickers DPH (10 kg). "C" etch, X250.

(B) Ti-13V-11Cr-3Al alloy; hot rolled, solution treated and aged condition. ASTM micro grain size number 1-2. Hardness 388 Vickers DPH (10 kg). "C" etch, X100.

PHD-56417-9-61

FIGURE 8

MICROSTRUCTURE IN UNWELDED HEAT TREATED BASE METAL SAMPLES OF TITANIUM ALLOYS FROM COMPANY F

("C" etch contains 1 ml HF, 25 ml HNO_3, 3 grams $Pb(NO_3)_2$ and water to make 100 cc)

(A) Ti-6Al-4V alloy, specimen W-4, notch at edge of weld, G_c fast fracture on right end.

(B) Ti-13V-11Cr-3Al alloy, specimen W-4, notch at edge of weld, G_c fast fracture on right end.

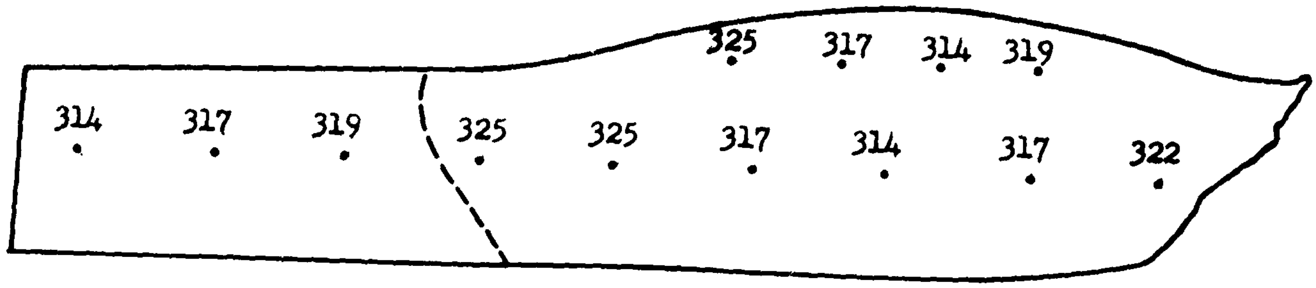
PHD-56415-9-61

FIGURE 9

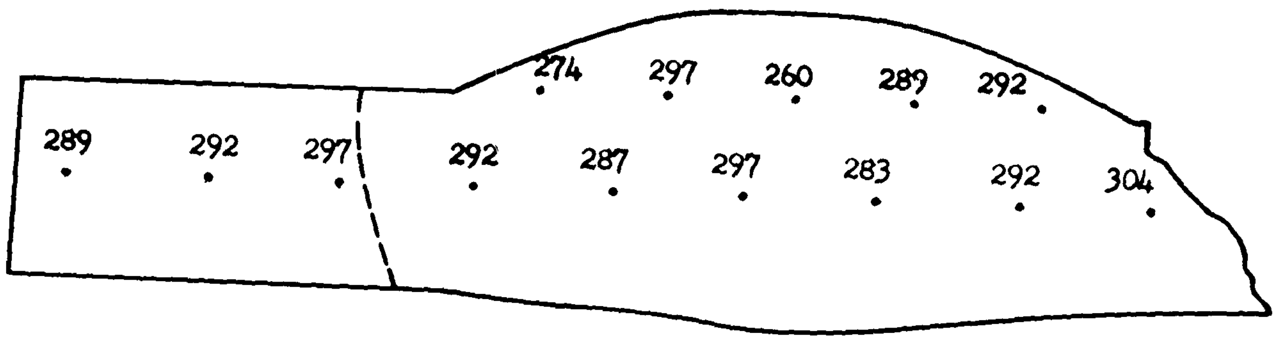
CROSS SECTIONS OF TYPICAL WELDS ETCHED TO SHOW GRAIN STRUCTURE IN WELDED TITANIUM ALLOY SAMPLES SUPPLIED BY COMPANY F

Hot rolled, annealed and welded

Face of weld at top, "C" etch, X8



(A) Ti-6Al-4V alloy, specimen W-4. (Photo, Figure 9A)



(B) Ti-13V-11Cr-3Al alloy, specimen W-4. (Photo, Figure 9B)

FIGURE 10

HARDNESS TESTS ACROSS WELDS IN WELDED TITANIUM ALLOY SAMPLES SUPPLIED BY COMPANY F

Vickers DPH Taken 2 mm Apart, 10 Kg Load, X3

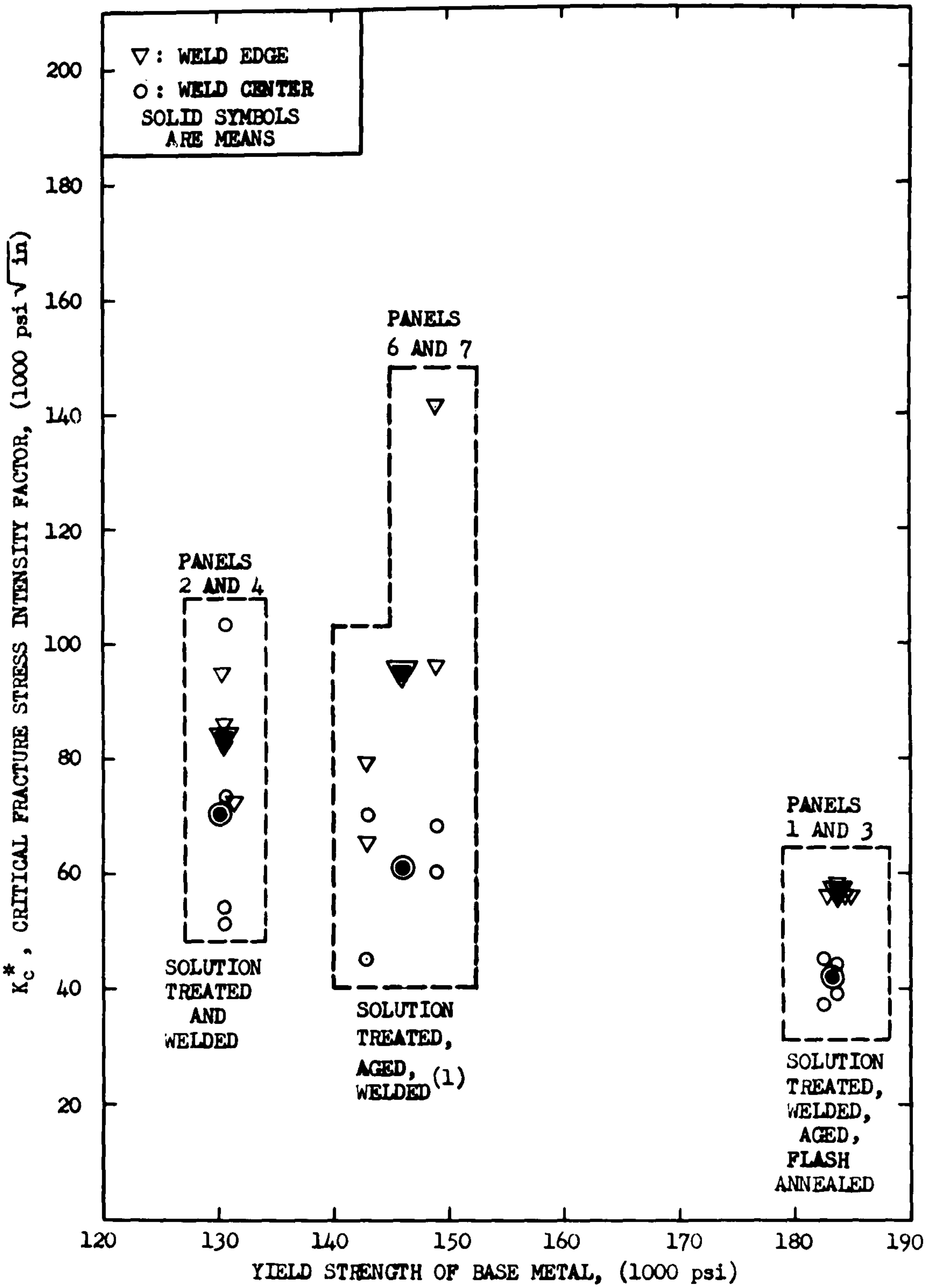


FIGURE 11

K_c^* CRITICAL FRACTURE STRESS INTENSITY FACTORS FOR WELDS OF Ti-13V-11Cr-3Al TITANIUM ALLOY SHEET, 0.125 INCH NOMINAL THICKNESS WITH INDICATED TREATMENTS, SAMPLES FROM COMPANY A

(1) Yield strengths were referred to hardness indications at the edge of the annealed weld rather than the yield strength of the aged base metal.

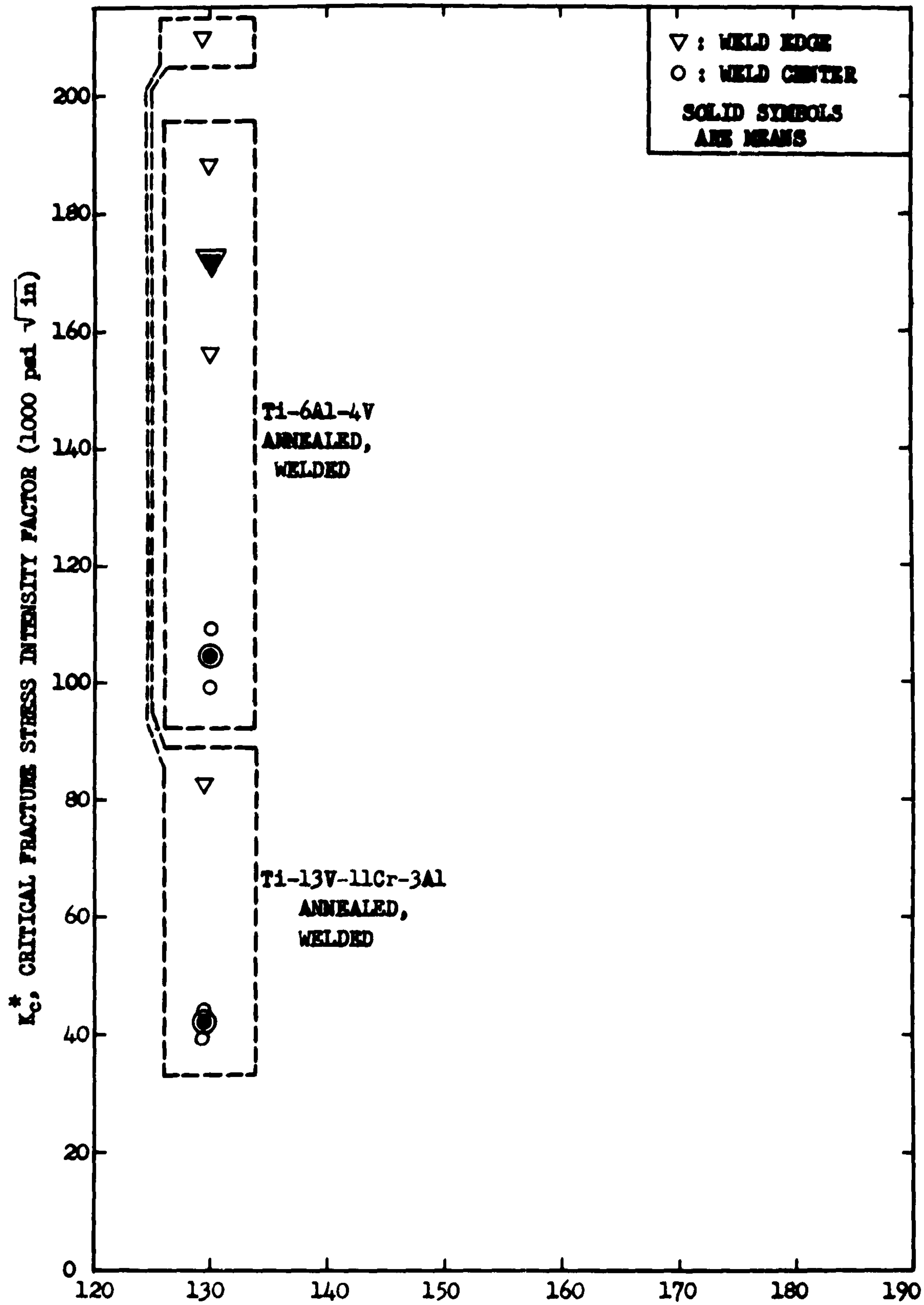


FIGURE 12

K_c^* CRITICAL FRACTURE STRESS INTENSITY FACTORS FOR WELDS OF Ti-6Al-4V AND Ti-13V-11Cr-3Al TITANIUM ALLOYS, 0.125 INCH NOMINAL THICKNESS, ANNEALED BASE METAL AS WELDED, SAMPLES FROM COMPANY F

(A) Broken pieces of specimen W-3 cemented together show fracture with normal G_c^* value of 475 in-lb/in^2. Fracture is entirely within fusion and heat affected zones where recrystallization occurred.

(B) Fracture at opposite edge of same weld in specimen W-4 gave high G_c^* value of 3100 in-lb/in^2. Fracture was concentrated at section reinforced by tough base metal unaffected by welding heat (arrow).

PHD-56416-9-61

FIGURE 13

CROSS SECTIONS ILLUSTRATE SOURCE OF HIGH FRACTURE TOUGHNESS ALONG ONE EDGE OF WELD IN Ti-13V-11Cr-3Al ALLOY FROM COMPANY F

Face of weld at top, "C" etch, X15

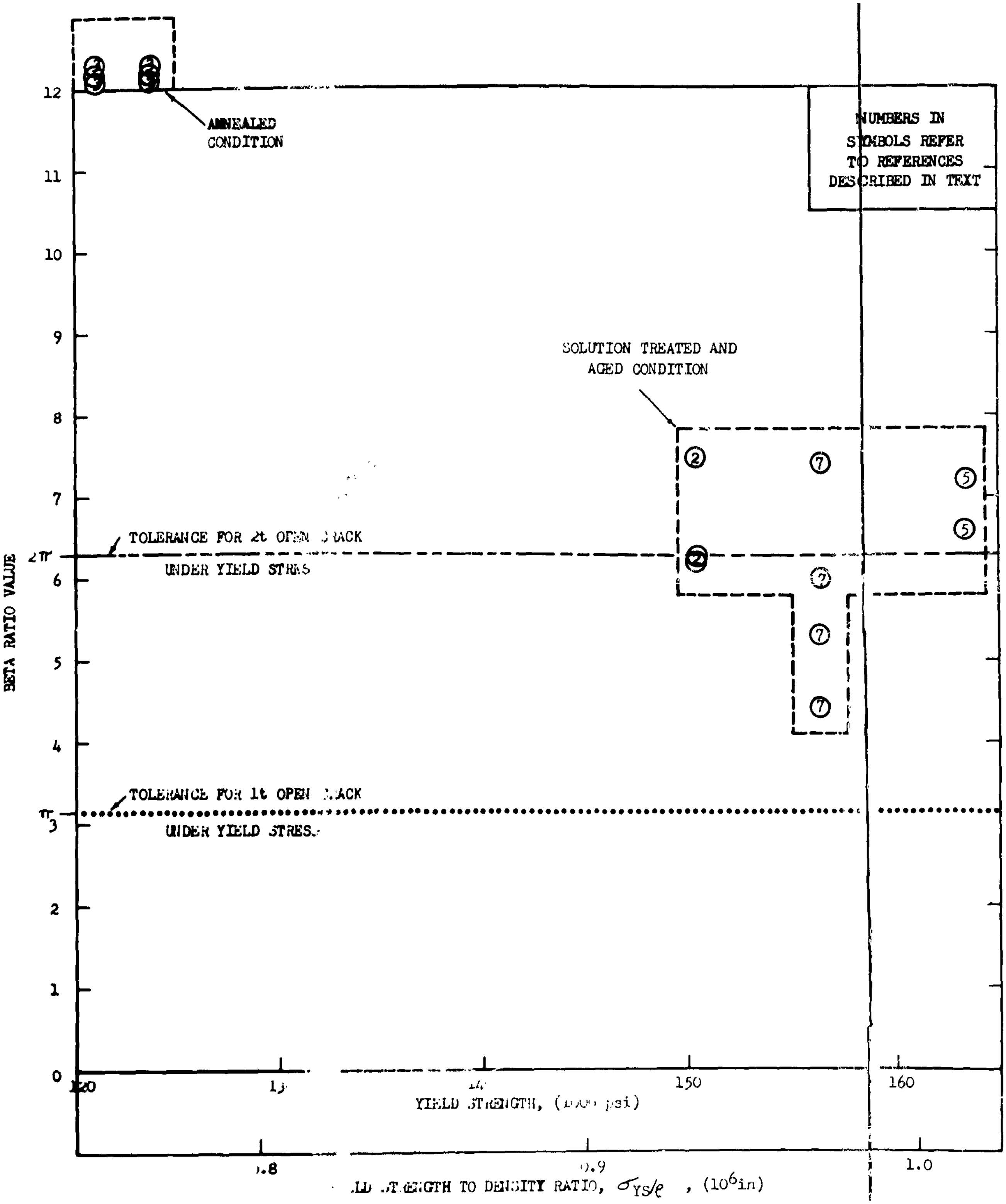


FIGURE 14

BET. [illegible] F OM G_c TESTS OF Ti-6Al-4V TITANIUM ALLOY SHEETS, [illegible] TO [illegible] INCH THICK, FROM ALL SOURCES

tandard ASTM trip Specimen, Size 3 by 12 Inches. entral Starting Slot 1 Inch Long Was Tipped With [illegible] hined Notches Having a Root Radius of [illegible] Inch.

imens ere Stressed in the Longitudinal Direction.

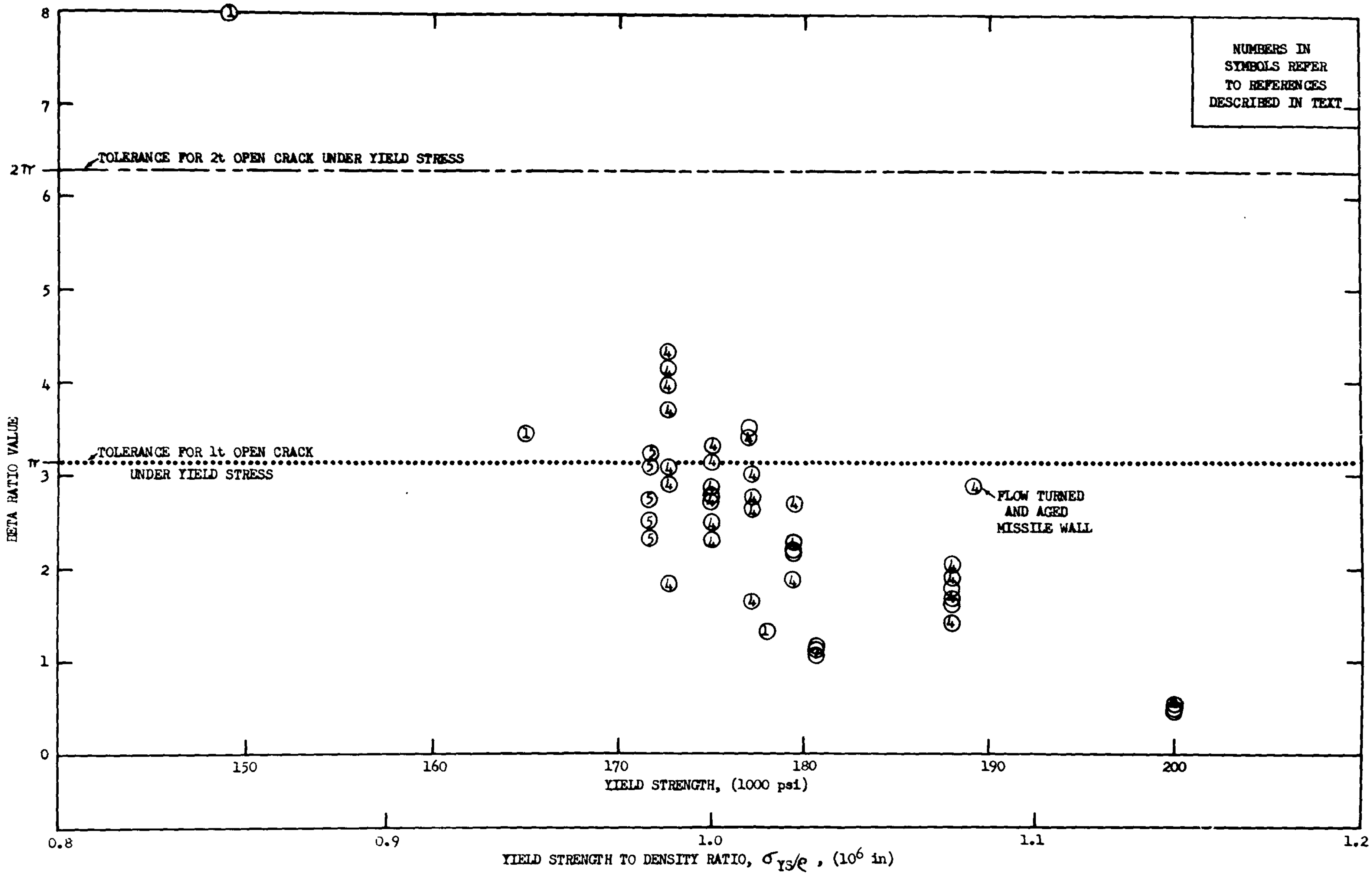


FIGURE 15

BETA VALUES FROM G_c TESTS OF Ti-13V-11Cr-3Al TITANIUM ALLOY SHEETS, 0.06 TO 0.12 INCH THICK, FROM ALL SOURCES

Standard ASTM Strip Specimen, Size 3 by 12 Inches.
Central Starting Slot 1 Inch Long Was Tipped With Machined Notches Having a Root Radius of 0.001 Inch.
Specimens Were Stressed in The Longitudinal Direction.

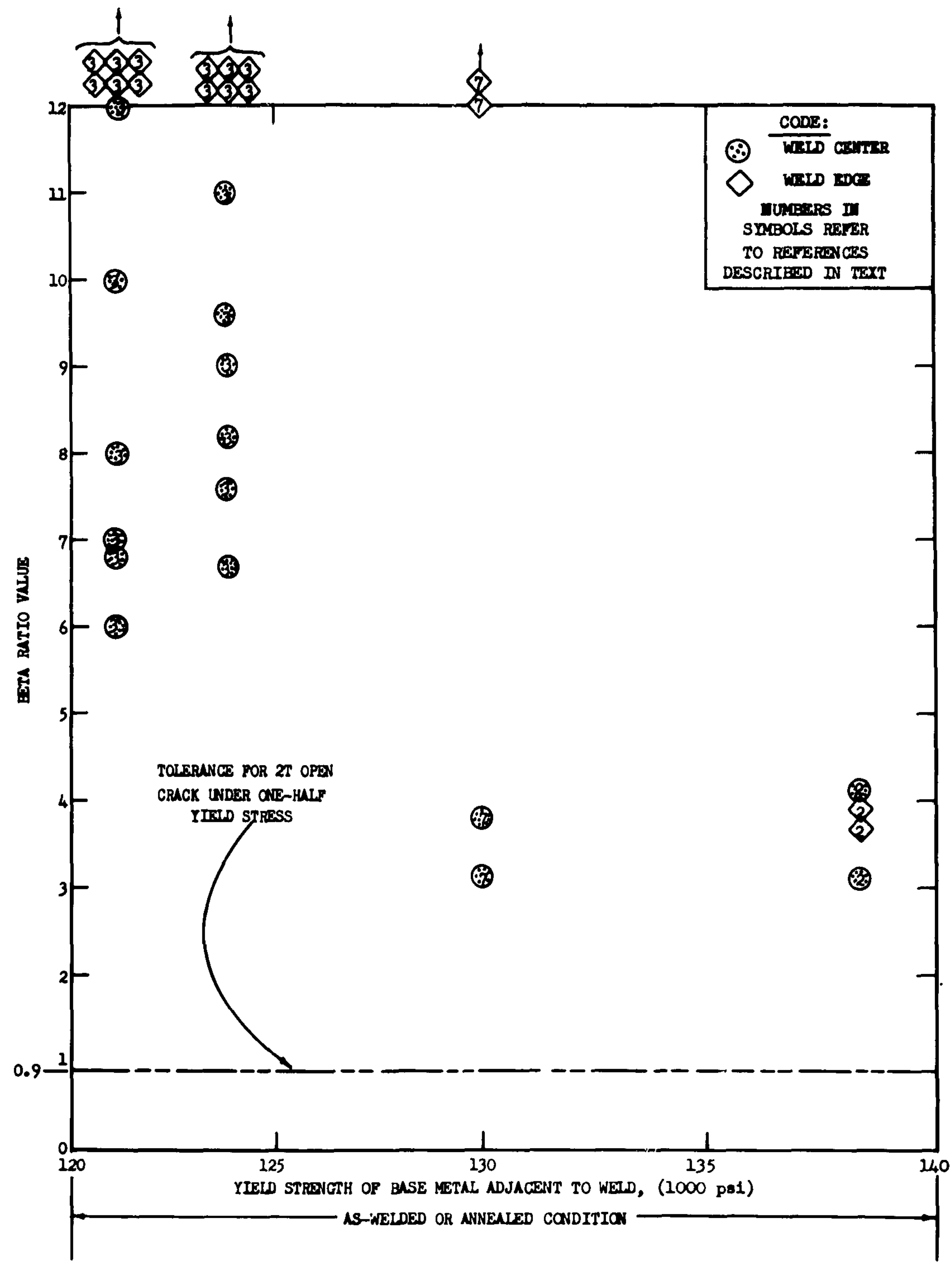


FIGURE 16

BETA VALUES FROM G_c TESTS ON WELDS IN Ti-6Al-4V SHEET, APPROXIMATELY 0.125 INCH THICK, FROM ALL SOURCES

A Beta of 0.9 Indicates Tolerance For a 2t Crack Under Axial Stress in a Circumferential Weld of a Cylinder Under Hoop Stress Equal to Yield Strength

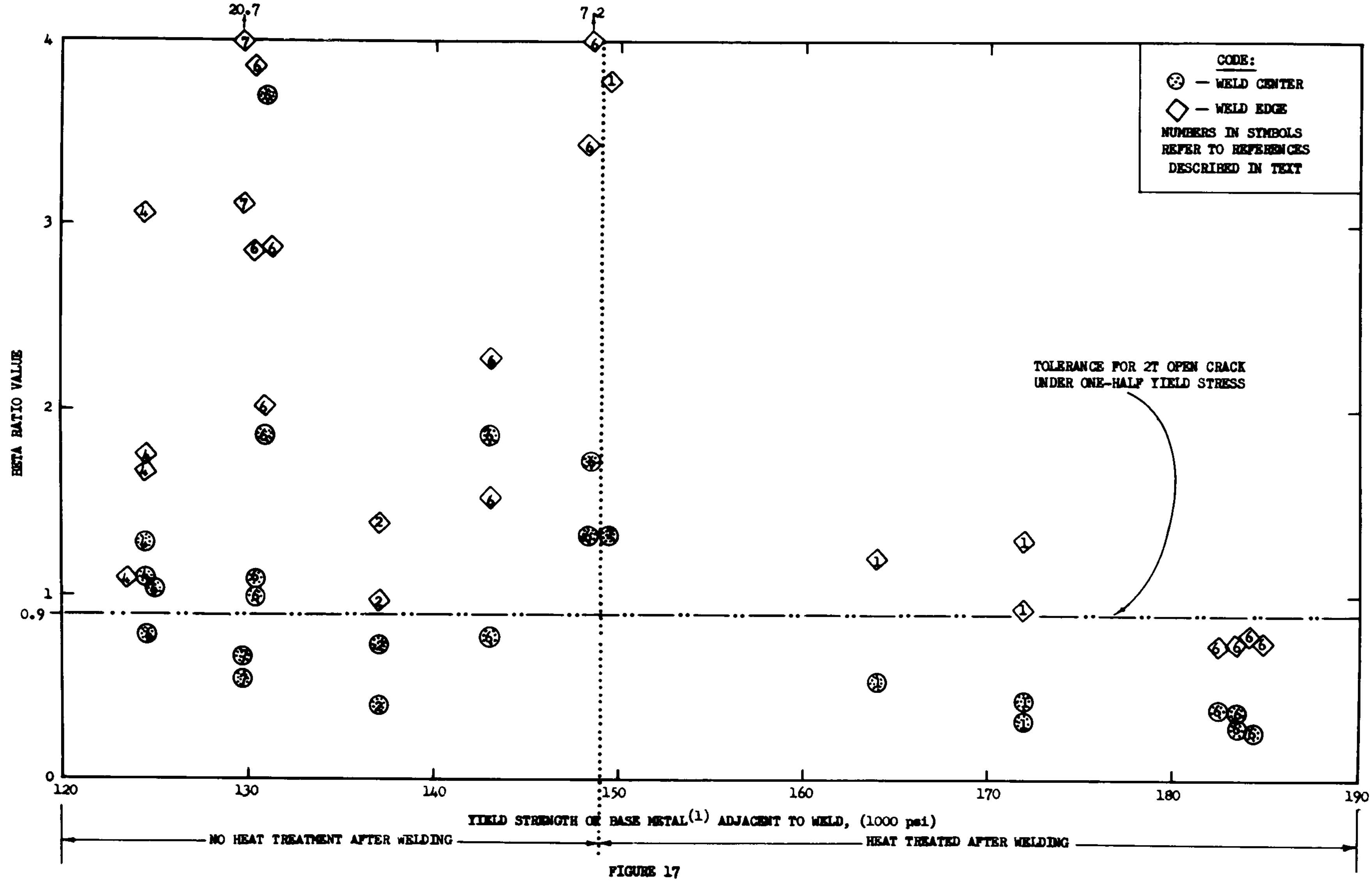


FIGURE 17

BETA VALUES FROM G_c TESTS ON WELDS IN Ti-13V-11Cr-3Al SHEET, APPROXIMATELY 0.125 INCH THICK, FROM ALL SOURCES

A Beta of 0.9 Indicates Tolerance For a 2t Crack Under Axial Stress in a Circumferential Weld of a Cylinder Under Hoop Stress Equal to Yield Strength

(1) No. 6 values at 143,000 and 149,000 psi yield strength were referred to hardness indications at the edge of the annealed weld rather than to the yield strength of the aged base metal.

APPENDIX B

FRACTURE WORK FACTORS IN $\mathfrak{D}_c$ TESTS OF Ti-13V-11Cr-3Al ALLOY FROM COMPANY A AND Ti-6Al-4V AND Ti-13V-11Cr-3Al ALLOYS FROM COMPANY F

DESCRIPTION OF SAMPLES

Company A, Welded Samples of Ti-13V-11Cr-3Al Alloy

Item	Size, Inches	Condition
1	0.125 x 12 x 13	Solution treated, welded, then aged 72 hours at 900°F plus 5 minutes at 1050°F.
3	0.125 x 12 x 13	Same as Item 1.
2	0.125 x 12 x 13	Solution treated and welded.
4	0.125 x 12 x 13	Same as Item 2.
6	0.125 x 12 x 13	Solution treated, aged 72 hours at 900°F, then welded.
7	0.125 x 12 x 13	Same as Item 6.

The welding practice was a special technique and the best available to Company A at the time (November 1960). Some spherical cavities like the one visible in Figure 4A were observed in the supplier's radiographic inspection. The cavities were small and probably could be classed as acceptable scattered porosity by soundness requirements for steel welds (MIL-R-11468(ORD)). Notch locations were chosen to minimize the presence of cavities in the fracture zone and no adverse effect on $\mathfrak{D}_c$ was detected. The welds on these small plates were experimental; production welding presumably would overcome the cavity problem.

Company F, Welded and Unwelded Samples of Titanium Alloys

Alloy	Size, Inches	Condition	Filler Wire
Ti-6Al-4V	0.125 x 12 x 15	Hot rolled, solution treated, aged and descaled.	Not welded
Ti-6Al-4V	0.125 x 12 x 15	Hot rolled, annealed and descaled, welded.	Ti-6Al-4V
Ti-13V-11Cr-3Al	0.125 x 12 x 15	Hot rolled, solution treated, aged and descaled.	Not welded
Ti-13V-11Cr-3Al	0.125 x 12 x 15	Hot rolled, annealed and descaled, welded.	Ti-13V-11Cr-3Al

On Company F samples, the principal rolling directions are given in Figure 7. The welding practice was a commercial type carried out under laboratory conditions.

Tensile Properties. Base-metal properties in the welded samples supplied by Company A are given in Table 2. Items 2 and 4 gave typical results for solution treated material. Items 6 and 7 were somewhat variable in response to the aging treatment. Different lots of alloy may be involved. It is customary to use the yield strength of the adjacent base metal in calculating properties of welds. Hardness test patterns across weld cross sections indicated that an adjustment of yield strength in the weld zone may be useful for some items.

The appearance of Ti-13V-11Cr-3Al tensile test fractures in Company A material can be summarized as follows.

Items	Yield Strength Level (psi)	Comments
2, 4	130,000	Fibrous, nearly full shear.
6, 7	160,000	Fine granular mixed with shear.
1, 3	180,000	Nearly flat granular fracture of fine texture.

TABLE 2

TENSILE PROPERTIES OF BASE METAL IN Ti-13V-11Cr-3Al ALLOY TEST SAMPLES FROM COMPANY A

Item	Condition	Thickness (in)	σ_{YS} Yield Strength (psi at 0.2% offset)	Tensile Strength (psi)	Elongation (% in 1 in.)	True Fracture Stress (psi)	Reduction of Area (%)	Rockwell C Hardness
1	Solution treated, welded, then aged 72 hrs. at 900°F plus 5 min. at 1050°F	0.127	183,500	204,600	5	223,000	8.5	45
3	Same as Item 1	0.123	182,300	200,300	6	222,900	10.5	44
2	Solution treated and welded	0.129	130,300	137,900	22	220,500	48.5	33.5
4	Same as Item 2	0.129	130,800	141,000	21	229,500	50.5	34
6	Solution treated, aged 72 hrs. at 900°F, then welded	0.128	155,300	177,900	9	204,300	14	40.5
7	Same as Item 6	0.119	168,100	199,700	5	219,700	9	44

These specimens had 5/16-inch width and 1-inch gauge length in the test area and were machined from broken halves of K_c specimens. Specimen axis was parallel to long side of K_c specimen.

True fracture stress was obtained by dividing load at instant of fracture by smallest cross-section area of fracture.

The results are averaged from two tests.

The base-metal properties of the samples from Company F are shown in Table 3. Tensile fractures had the following appearance.

Alloy	Yield Strength Level (psi)	Comments
Ti-6Al-4V	130,000	Fibrous, full shear.
	155,000	Fine granular with about 60 percent shear.
Ti-13V-11Cr-3Al	130,000	Coarse shear, somewhat granular
	180,000	Granular with some shear at free surfaces.

The fractures of smooth tensile tests may differ in appearance from fractures associated with the sharp notch in the K_{Ic} test.

Fracture occurred at a distance of one-half inch or more from the weld edge in the tensile tests of the welded samples of both alloys from Company F. This is a good indication that, in the soft annealed base metal, the welds developed 100 percent efficiency.

The strength-weight factors of the unwelded samples from Company F can be rated by the ratio of yield strength to density.

Alloy	ρ Density (lb/in^3)	σ_{YS} Yield Strength (psi)	Ratio σ_{YS}/ρ
Ti-6Al-4V	0.161	156,600	970,000
Ti-13V-11Cr-3Al	0.175	180,700	1,030,000

These values are near the ratio of one million desired in the cylinder wall of a rocket case.

Fracture Test Specimens. These were flat specimens three inches wide by twelve inches long. Pin loading was applied to the specimens through one-inch holes on centers 2-1/8 inches from specimen ends. The welded panels were cut and notched as shown in Figures 1 and 7. The transverse central notch one inch long was prepared by grinding a starting slot and finishing with special files in a mechanical filing machine. The notch root radii were measured with a projector comparator. All radii were 0.001 inch or less.

TABLE 3

TENSILE PROPERTIES OF BASE METAL IN WELDED AND UNWELDED TITANIUM ALLOY SAMPLES SUPPLIED BY COMPANY F

Alloy	Condition	Test Direction	Thickness (in)	σ_{YS} Yield Strength (psi at 0.2% offset)	Tensile Strength (psi)	Elongation (% in 2 in.)	Rockwell C Hardness
Ti-6Al-4V	Hot rolled, solution treated and aged descaled (no weld)	Long.	0.128	156,600	167,600	9.5	40.5
Ti-6Al-4V	Hot rolled, annealed and descaled, welded	Trans.	0.121	130,900	141,400	9	34
Ti-13V-11Cr-3Al	Hot rolled, solution treated aged and descaled (no weld)	Long.	0.121	180,700	194,100	3	43
Ti-13V-11Cr-3Al	Hot rolled, annealed and descaled, welded	Trans.	0.129	129,700	137,900	9.5	31

Standard tensile specimens were used, located as shown in Figure 7.

In specimens containing a weld, fracture occurred 1/2 inch or more from weld edge.

The results are averaged from two tests.

Fracture Characteristics in the $\mathcal{J}_c$ Test. Percent shear was measured at the halfway point along $\mathcal{J}_c$ fast fracture. The values are visual estimates based on examination under a low power microscope. The appearance of the $\mathcal{J}_c$ fractures was strongly dependent on the alloy type. The Ti-6Al-4V alloy from Company F developed 100 percent shear in both welded and unwelded tests. Lower shear values were obtained in the beta alloy, Ti-13V-11Cr-3Al (Tables 4 and 5). The typical coarse granular fracture in the weld zone introduced uncertainty but visual estimates could be made within about a 5 percent tolerance. The averages of all-beta tests were 27 percent shear at the edge and 13 percent shear in the weld center. Unusually high values of shear (40 percent) were observed in weld edge samples 7-2 from Company A and W-2 from Company F but none of the weld center tests exceeded 20 percent shear.

Calculations and $\mathcal{J}_c$ Results. The data from the $\mathcal{J}_c$ tests are given in Tables 4 and 5. The formulas used in calculations are given below.

$\mathcal{J}_c$*: Use graph with θ as abscissa, tan θ as ordinate, plotted in radians. Plot first point with coordinates: $\pi\frac{a}{W}$, 0. Plot second point with coordinates: $\pi\frac{a}{W} + \frac{\sigma_o^2}{\sigma_{YS}^2}$, 2. Draw straight line through points. Intersection with tan θ curve gives θ in

$$\mathcal{J}_c{*} = \frac{\sigma_o^2 \, W \tan\theta}{E} .$$

The following moduli were used.

Alloy	Condition	E Modulus
Ti-6Al-4V	-----	16.5×10^6 psi
Ti-13V-11Cr-3Al	Annealed	14.2×10^6 psi
Ti-13V-11Cr-3Al	Aged	14.8×10^6 psi

$$K_c^* = \sqrt{E\mathfrak{G}_c^*}, \quad \sigma_{net} = \frac{P}{(W-2a)t}, \quad \sigma_o = \frac{P}{Wt}$$

where W = width of specimen, t = thickness of sheet, 2a = critical crack length from ink stain.

Beta ratio,

$$\beta = \frac{E\,\mathfrak{G}_c^*}{t\ \sigma_{YS}^2}$$

$\mathfrak{G}_{Nc}$ was determined by the acoustic method described in NWL Report No. 1779:

$\mathfrak{G}_{Nc} = \frac{\sigma^2 W}{E} \tan \frac{\pi\, a_o}{W}$ where σ is the gross stress when the first crack sound is heard.

Crack length calculation for Figures 14 through 17:

The beta value for critical crack propagation is defined

$\beta_c = \frac{E\,\mathfrak{G}_c^*}{t\ \sigma_{YS}^2}$. A general formula for the half-length a of the open critical crack is $a = \frac{E\,\mathfrak{G}_c^*(2\sigma_{YS}^2 - \sigma^2)}{2\pi\ \sigma_{YS}^2\ \sigma^2}$.

The desired minimum length tolerance in units of sheet thickness for an open crack under stress is taken to be 2t so a = t. In the case of hoop stress $\sigma = \sigma_{YS}$ and the general formula reduces to:

$$a = \frac{E\,\mathfrak{G}_c^*}{2\pi\ \sigma_{YS}^2} = t$$

Rearranging and substituting β_c the result is that $\beta_c = 2\pi$ for a crack length tolerance of 2t. Under hoop stress therefore, the beta ratio value divided by pi gives crack tolerance in units of sheet thickness (Figures 14 and 15).

In the case of axial stress across a girth weld, σ in the general formula becomes $\sigma_{YS/2}$ with the result:

$$a = \frac{7\ E\ \mathcal{D}_c\ *}{2\pi\ \sigma_{YS}{}^2} = t$$

Factoring out β_c , $\beta_c = \frac{2\pi}{7} = 0.9$ for a crack length tolerance of 2t, or 0.45 for 1t. Dividing beta value by 0.45 gives the crack tolerance in units of thickness for girth welds under axial stress (Figures 16 and 17).

TABLE 4 SUMMARY OF FRACTURE TOUGHNESS TESTS ON WELDED SPECIMENS OF Ti-13V-11Cr-3Al ALLOY FROM COMPANY A

Condition	Notch Location	Specimen Number	σ_{YS} Yield Strength (psi)	Thickness (in)	Width (in)	$2a_o$ Notch Length (in)	P Maximum Load (lb)	2a Crack Length (in)	σ_{net} Net Section Stress (psi)	$\mathcal{G}_c^*$ Fracture Toughness (in-lb/in^2)	K_{c1}^* Stress Intensity (1000 psi $\sqrt{in}$)	Net Section Ratio σ_{net}/σ_{YS}	Shear in Fast Fracture (%)	$\mathcal{G}_{Nc}$ Crack Initiation (in-lb/in^2)	β Beta Value
Solution treated, welded, then aged 72 hrs. at 900°F plus 5 min. at 1050°F	Weld center	1-1	183,500	.154	2.988	1.00	11,000	1.32	43,000	98	39	.234	20	33	.29
		1-4	183,500	.157	2.700	.99	10,500	1.45	53,800	129	44	.293	20	—	.37
						Average	10,800	1.39	48,400	114	42	.264	20	33	.33
	Weld center	3-2	182,300	.160	3.011	.99	12,800	1.44	51,000	137	45	.280	15	43	.38
		3-3	182,300	.158	3.009	.99	12,100	1.19	42,200	97	37	.231	10	30	.26
						Average	12,500	1.32	46,600	117	41	.256	13	37	.32
	Weld edge	1-2	183,500	.126	3.027	1.01	12,600	1.42	62,400	211	56	.340	15	44	.74
		1-3	183,500	.127	2.992	1.01	12,600	1.48	65,800	228	58	.359	15	28	.79
						Average	12,600	1.45	64,100	220	57	.350	15	36	.77
	Weld edge	3-1	182,300	.125	3.029	1.00	12,300	1.44	61,900	207	56	.340	20	50	.75
		3-4	182,300	.129	3.003	1.00	13,200	1.35	62,100	209	56	.341	25	43	.73
						Average	12,800	1.40	62,000	208	56	.341	23	47	.74
Solution treated and welded	Weld center	2-1	130,300	.157	3.005	.99	16,200	1.17	56,300	185	51	.432	5	73	.98
		2-4	130,300	.158	2.956	1.01	17,100	1.14	59,600	205	54	.457	15	—	1.09
						Average	16,700	1.16	58,000	195	53	.445	10	73	1.03
	Weld center	4-1	130,800	.168	3.031	.99	33,100	1.13	103,600	748	103	.792	15	95	3.69
		4-2	130,800	.167	3.028	.99	23,300	1.18	75,400	370	73	.576	10	89	1.87
						Average	28,200	1.16	89,500	559	88	.684	13	92	2.78
	Weld edge	2-2	130,300	.135	3.000	1.00	24,200	1.15	96,800	627	94	.743	25	37	3.86
		2-3	130,300	.135	3.003	1.01	21,200	1.15	84,800	456	81	.651	30	174	2.86
						Average	22,700	1.15	90,800	542	88	.697	28	106	3.36
	Weld edge	4-3	130,800	.149	3.006	1.00	20,600	1.14	74,100	368	72	.567	30	—	2.03
		4-4	130,800	.146	3.014	1.00	24,000	1.17	89,200	512	85	.682	25	105	2.89
						Average	22,300	1.16	81,700	440	79	.625	28	105	2.46
Solution treated, aged 72 hrs. at 900°F, then welded	Weld center	6-3	155,300	.153	2.994	1.00	20,000	1.25	74,900	332	69	(.482)(1)	20	27	(1.27)(1)
		6-4	155,300	.152	3.008	1.00	14,300	1.11	49,400	140	45	(.318)	10	96	(.55)
						Average	17,200	1.18	62,200	236	57	(.400)	15	62	(.91)
	Weld center	7-3	168,100	.157	3.005	1.00	19,700	1.29	73,200	312	66	(.435)	10	39	(.98)
		7-4	168,100	.156	3.006	1.01	17,900	1.25	65,300	236	58	(.388)	15	19	(.76)
						Average	18,800	1.27	69,300	274	62	(.412)	13	29	(.87)
	Weld edge	6-1	155,300	.135	3.027	.99	17,700	1.17	70,500	296	65	(.454)	25	50	(1.30)
		6-2	155,300	.134	2.994	1.00	20,000	1.23	84,700	432	78	(.545)	30	208	(1.88)
						Average	18,900	1.20	77,600	364	72	(.500)	28	129	(1.59)
	Weld edge	7-1	168,100	.121	3.004	1.02	22,700	1.14	100,400	626	94	(.597)	25	149	(2.58)
		7-2	168,100	.124	2.997	1.01	31,500	1.14	137,000	1296	136	(.815)	40	79	(5.28)
						Average	27,100	1.14	118,700	961	115	(.706)	33	114	(3.93)

(1) These values are based on yield strength of adjacent base metal. More probable values are given in Table 1 based on yield strength in weld zone estimated from the hardness patterns.

TABLE 5

SUMMARY OF FRACTURE TOUGHNESS TESTS ON Ti-6Al-4V AND Ti-13V-11Cr-3Al ALLOYS FROM COMPANY F

Alloy	Condition	Notch Location	Specimen Number	σ_{YS} Yield Strength (psi)	Thickness (in)	Width (in)	$2a_o$ Notch Length (in)	P Maximum Load (lb)	2a Crack Length (in)	σ_{net} Net Section Stress (psi)	$\mathcal{G}_c^*$ Fracture Toughness (in-lb/in^2)	K^*_{cl} Stress Intensity (1000 psi $\sqrt{in}$)	Net Section Ratio σ_{net}/σ_{YS}	Shear(1) in Fast Fracture (%)	$\mathcal{G}_{Nc}$(2) Crack Initiation (in-lb/in^2)	β Beta Value
Ti-6Al-4V	Solution treated and aged	Base metal, long. test	L-1	156,600	.123	2.986	1.005	17,700	1.90	131,900	807	115	.842	100	227	4.38
			L-2	156,600	.124	3.052	1.000	20,500	1.93	147,300	1103	135	.940	100	279	5.99
			L-3	156,600	.124	3.034	1.020	20,200	1.86	138,200	973	127	.882	100	300	5.31
			L-4	156,600	.123	3.030	1.020	19,700	2.04	161,300	1341	149	1.030	100	278	7.36
							Average	19,500	1.93	144,700	1056	132	.924	100	271	5.76
Ti-6Al-4V	Annealed, as welded	Weld center	W-1	130,900	.186	3.045	.990	32,300	1.47	110,200	722	109	.847	100	334	3.78
			W-2	130,900	.189	3.035	.995	32,100	1.37	101,900	598	99	.783	100	172	3.07
							Average	32,200	1.42	106,100	660	104	.841	100	253	3.43
		Weld edge	W-3	130,900	.122	3.046	1.01	26,100	1.66	154,400	>2138	188	1.187	100	486	17.14
			W-4	130,900	.122	3.043	1.01	25,700	1.53	138,900	1479	156	1.068	100	210	11.80
							Average	25,900	1.60	146,700	1830	172	1.128	100	348	14.47
Ti-13V-11Cr-3Al	Solution treated and aged	Base metal, long. test	L-1	180,700	.124	2.993	1.005	13,600	1.45	71,300	284	65	.395	20	48	1.04
			L-2	180,700	.124	3.025	1.015	14,400	1.44	73,100	305	67	.405	20	111	1.11
			L-3	180,700	.123	3.050	1.010	14,800	1.38	72,100	300	66	.399	20	—	1.08
							Average	14,300	1.42	72,200	296	66	.400	20	80	1.08
		Base metal, trans. test	T-1	180,700	.123	3.036	1.005	12,800	1.28	59,400	204	54	.329	20	52	.73
Ti-13V-11Cr-3Al	Annealed, as welded	Weld center	W-1	129,700	.167	3.026	.980	13,300	1.17	42,900	108	39	.331	10	56	.54
			W-2	129,700	.175	3.066	.990	17,400	1.02	48,600	136	44	.375	10	13	.66
							Average	15,350	1.10	45,800	122	42	.353	10	35	.60
		Weld edge	W-3	129,700	.128	3.052	1.005	20,600	1.17	85,500	475	82	.659	30	37	3.12
			W-4	129,700	.127	3.038	1.000	33,600	1.41	162,300	>3112	210	1.251	40	25	20.65
							Average	27,100	1.29	123,900	1794	146	.955	35	31	11.89

(1) VISUAL ESTIMATE
(2) FROM ACOUSTIC DETERMINATION OF LOAD FOR CRACK INITIATION

APPENDIX C

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(NWL Report No. 1798)
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3. Welds - Fracture
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